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SETTLEMENT OF SOIL DUE TO WATER UPTAKE BY PLANT ROOTS

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SUMMARY

The settlement of soil occurs whenever there is an increase in effective confining stress. The withdrawal of water by plant roots results in a change in water pressure and moisture content in the soil. The variation in the moisture content leads to a change in the effective stress that causes a decrease in porosity which eventually results in the settlement of soil. The driving force for the uptake of water by the roots is the difference in the plant water and soil water potential existing between the soil solution adjacent to the roots and the root xylem. In case of transpiring plants, this driving force is mainly due to the tension (negative pressure) produced in the roots. A finite element solution of the governing equation yields the variation of moisture content with depth and the total settlement of the soil column due to the extraction of water by the plant roots. The simulated results indicate the damaging situation due to changes in the soil moisture content on account of transpiring trees and plants grown around the perimeter of structures.

KEY WORDS: settlement; extraction function; water uptake; finite element; transpiration

INTRODUCTION

The problem of soil settlement is significant for expansive soils that are known for their moisture sensitiveness. Such soils can cause significant damage on account of their swell–shrink behaviour. If trees and shrubs are located close to buildings the roots and rootlets of trees and plants could extract moisture from the soil beneath the shallow foundations which can cause the clays to shrink, resulting in the settlement of structures.[1] There have been several cases where removal of large trees from the proximity of buildings has led to the expansion of soil due to the increase in the moisture content to its natural state.[2] Furthermore, studies conducted on large, broad-leaf, deciduous trees located near structures have shown that great changes in the moisture take place in the rooting zone causing damage to the structures in both the arid and humid areas.[3] Likewise, investigations on 36 different trees covering a range of tree species and clay types indicate that the amount of soil movement is a function of clay shrinkage characteristics.[4,5] Similarly, large pepper trees have been found to damage an apartment complex due to water withdrawal by their roots.[6]

The problem of settlement of soil due to water uptake by roots is more important during periods of drought when the quantity of water used by such trees and shrubs during transpiration exceeds the amount of rainfall in the area containing the tree roots. It is these non-uniform

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moisture changes and soil heterogeneities causing the uneven soil movements that damage shallow foundations, structures, or pavements. Planting trees and shrubs away from such structures may help prevent damage from settlement due to water uptake by plant roots.

An effort has been made in this study to develop a conceptual and simple macroscopic root water uptake model that simulates water uptake by roots using a realistic root extraction function for plants. A simplified root distribution equation that predicts the root growth with time and space is also incorporated in the model. The root system in this study is taken as a single unit (macroscopic study) and the effect of individual roots (microscopic study) is not considered because it is very difficult to measure the time dependent geometry of the root system. Thus the entire root zone is assumed to extract moisture from small differential volumes of the root zone at some rate. The study is applicable to plants that have a rooting depth of about 1 m below he ground surface and can be extended to cases of large trees or shrubs that may extract more water from the soil beneath the structures.

Incorporating a root extraction (sink) term in the mass balance equation for water in one dimension for an unsaturated soil column yields the partial differential equation that governs the moisture distribution movement along the vertical soil column. The total amount of water extracted by the roots can be determined by conducting a simple mass balance of moisture content over the entire domain. Then, using the equilibrium equation for unsaturated porous media along with the Terzaghi's definition of effective stress for unsaturated soils, an estimate of the total settlement in the soil column is obtained assuming a one-dimensional vertical compressibility of soil matrix. The changes in the incremental total stress due to the removal of soil moisture from the voids is also assumed in the model.[7] This excess total stress which is assumed to be due to the change in weight above a point can be calculated numerically by integrating the change in the moisture content from that point to the ground surface in the unsaturated soil column.

The porous medium in this study is assumed to be homogeneous and isotropic. In the formulation, the effect of inter-root competition for water is not considered. Also, it is assumed that the root hair does not affect the uptake of water by the roots. The water uptake by the roots is zero, when the soil is wetter than a certain anaerobiosis point and drier than the wilting point. Thus, it is assumed that the uptake is a constant maximum when the water pressure head in soil is between the said two points. Furthermore we are interested only in the amount of water that the plant extracts from the soil and hence the study does not account for the translocation of water to the other parts of the plant.

GOVERNING EQUATIONS

The mass balance equation for water in one dimension with a root water extraction term can be written as[8]

$$\frac{\partial h}{\partial h} = \frac{1}{c(h)}\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - \frac{S(z,t)}{c(h)} \tag{1}$$

where $S(z, t)$ is the root water extraction function expressed as the volume of water per unit volume of soil per unit time. $c(h)$ is the soil moisture capacity defined as $\partial\theta/\partial h$ where θ is the volumetric moisture content and h is the soil water pressure head. $K(h)$ is the pressure head-dependent hydraulic conductivity and z is the soil depth taken to be positive upwards.

The root water extraction function is a sink term in equation (1) which represents the volume of water withdrawn by plant roots. There are many expressions for this function available in the literature[9] and the one suggested by Rama Prasad[10] has been adopted in this model. This model was verified for ample soil moisture conditions utilizing the data for five crops. Thus,

$$S(z,t) = \frac{2T_{\mathrm{p}}(t)}{Z_{\mathrm{r}_{\max}}}\,\alpha(h)\left[1 - \frac{Z_{\mathrm{r}}}{Z_{\mathrm{r}_{\max}}}\right] \tag{2}$$

where $S(z,t)$ is the root water uptake (extraction) function. T_{p} is the potential transpiration rate and Z_{r} is the rooting depth. $Z_{r\max}$ is the maximum rooting depth and $\alpha(h)$ is the pressure head-dependent reduction factor which is a function of soil water pressure head and the hydraulic conductivity in the root zone. The extraction term is reduced by this reduction factor when the soil moisture is limiting.[11]

Rama Prasad[10] modified the extraction function suggested by Hoogland[12] and expressed $S(z,t)$ such that the root water uptake is zero at the bottom of the root zone. The function was proportional to the potential transcription rate T_{p} and the rooting depth Z_{r}.

Many empirical expressions that predict the temporal variation of root depth exist in literature, but the one developed by Borg and Grimes[13] has been adopted in this study since it has been tested on 150 field observation during the growing seasons for 48 crop species. The simusoidal root growth function derived after an extensive regression analysis is

$$Z_{\mathrm{r}} = Z_{\mathrm{r}\max}\left[0{\cdot}5 + 0{\cdot}5\,\mathrm{Sin}\left(3{\cdot}303\,\frac{\mathrm{DAP}}{\mathrm{DTM}} - 1{\cdot}47\right)\right] \tag{3}$$

where DAP and DTM are the days after planting and days to maturity of the crop under consideration. This empirical relation does not take into account the root distribution with depth. Also, equation (3) is a simple root growth expression and is applicable to conditions of slight to moderate root growth inhibition.

The governing mass balance equation (1) is to be coupled with the equilibrium equation to determine the effective stress due to the variation of moisture content in the soil that eventually results in settlement.

The effective stress for the unsaturated soils is defined by the equation

$$\bar{\sigma}_z^{\mathrm{e}} - S_{\mathrm{w}} p^{\mathrm{e}} = \sigma_z^{\mathrm{e}} \tag{4}$$

where $\bar{\sigma}_z^{\mathrm{e}}$ and σ_z^{e} are the excess effective stress and total stress, respectively, p^{e} represents the excess pore water pressure. The superscript 'e' indicates all excess values that are equal to the difference between the current values and the initial (steady) ones. S_{w} is the degree of saturation and is related to the moisture content in the unsaturated soil and the porosity of the soil by the expression ($\theta = nS_{\mathrm{w}}$). A change in the effective stress produces a deformation of the soil matrix, resulting in a change in porosity.

The porosity (n) of the soil matrix at any instant of time is expressed by Mathur.[14]

$$n = n_0 + \alpha'(1 - n_0)\,[\sigma_z^{\mathrm{e}}|_z + p^{\mathrm{e}}] \tag{5}$$

when n_0 is the initial porosity and 'α' is the vertical matrix compressibility defined as

$$\alpha' = 1/(\lambda + 2G) \tag{6}$$

By assuming a homogeneous, isotropic and elastic soil, Hooke's law can be used to relate the vertical effective stress to vertical displacement as[14]

$$\bar{\sigma}_z^{\mathrm{e}} = (\lambda + 2G)\frac{\partial U_z}{\partial z} \tag{7}$$

where U_z is the settlement (vertical displacement) of soil at the depth z in the soil profile and is assumed to be zero initially.

At any point z in the soil domain, the change in the moisture content $\Delta\theta|_z$ due to the uptake of water by the roots results in the variation of total stress due to the change in the weight of the soil above that point,[15] thus

$$\sigma_z^{\mathrm{e}}|_z = \int_z^{\text{ground surface}} \Delta\theta|_z \gamma_{\mathrm{w}} \, \mathrm{d}z \tag{8}$$

where γ_{w} is the specific weight of water.

The change in excess total stress is computed from equation (8) at any point after the solution of equation (1) which yields the temporal and spatial variation of h (or θ). Knowing S_{w} and p^{e}, the excess effective stress is computed from equation (4) and U_z (settlement) from equation (7). The change in porosity is incorporated in the model with the use of equation (5). Since the volumetric moisture content and the hydraulic conductivity are non-linear functions of pressure head h, explicit expressions for the retention curve that relate h to θ and hydraulic conductivity curve relating K to h (or θ), respectively, are required in the analysis. The expressions are determined from the experimental data of Van Genuchten[16] and for this particular soil are taken to be continuous over the entire range of pressure heads. Thus,

$$\theta(h) = \theta_{\mathrm{r}} + \frac{\theta_{\mathrm{s}} - \theta_{\mathrm{r}}}{(1 + |ah|^{n})^{m}} \quad \text{for } \theta_{\mathrm{r}} \leqslant \theta \leqslant \theta_{\mathrm{s}} \tag{9}$$

and

$$K(h) = K_{\mathrm{s}} \frac{[(1 + |ah|^{n'})^{m} - |ah|^{n'-1}]^2}{(1 + |ah|^{n'})^{m(l+2)}} \tag{10}$$

where θ_{s} and θ_{r} are the saturated and residual moisture content, respectively, and a, n' and m are the empirical shape parameters estimated by fitting equations (9) and (10) to the experimental data. K_{s} is the saturated hydraulic conductivity, l is a soil specific parameter (generally assumed to be 0·5) and $m = 1 - 1/n'$.

Equations (1)–(10) form a complete set of governing equations which are non-linear partial differential equations, thus an analytical solution is not possible and a numerical method to obtain the solution needs to be applied. The governing equation (1) is subjected to initial and boundary conditions to obtain a mathematical solution for the non-steady moisture movement in the soil profile. The differential equation is subjected to a prescribed initial head (or moisture content) and a flux boundary at the surface that is defined on a 24 h basis in terms of computed potential evaporation, while the lower boundary is either a zero flux conditions or a prescribed pressure head. Thus initially,

$$h(z, 0) = h_0(z, 0) \quad \text{for } \theta_{\mathrm{r}} \leqslant \theta \leqslant \theta_{\mathrm{s}} \tag{11}$$

where $h_0(z, 0)$ is the prescribed head in the soil profile. Likewise

$$k(h)\left[\frac{\partial h}{\partial z} + 1\right] = q_t(t) \tag{12}$$

is the prescribed flux boundary condition applied to the upper boundary of the domain where $q_t(t)$ is the specified water flux into the soil during time t.

Since the water table was considered to be very low, the lower boundary condition was taken to be

$$h(L, t) = h_b(t) \quad \text{for } t \geqslant 0$$

where $h_b(t)$ is the specified soil water pressure head at that location.

RESULTS AND DISCUSSIONS

The governing equation (1) in one dimension (vertical) is numerically solved by the finite element technique using the Galerkin's method. The resulting set of non-linear simultaneous equations were solved iteratively using the Gauss elimination technique to obtain the pressure head at different times and depth of the soil profile. The soil and model parameters are presented in Table I. The simulation for the first 100 h was carried out taking a time step of 0.01 h after which it was increased to 0·1 h. Initially the pressure head in the entire soil column was assumed to be at − 300 cm of water. A total of 45 cm of water was applied over a period of 100 days at the top boundary. The bottom boundary was maintained at a constant suction head of − 300 cm of water assuming the water table to be very low.

Table I. Model and soil parameters

Height of soil column	= 120 cm
Number of elements	= 24
Initial porosity, n_0	= 0·4158
Transpiration rate T_p	= 2·5 cm/day
Lame's constant, λ	= $4{\cdot}47 \times 10^7$ N/m^2
Lame's constant, G	= $4{\cdot}47 \times 10^7$ N/m^2
Water flux into soil, q_t	= 0·45 cm/day
Residual moisture content, θ_r	= 0·11
Saturated moisture content, θ_s	= 0·4158
Saturated hydraulic conductivity, K_s	= 0·521 cm/h
Empirical shape factor, a	= 0·0104
Soil specific parameter, l	= 0·5
Empirical shape factor, n	= 1·3954
Empirical shape factor, m	= 0·2834
Pressure head dependent	
Reduction function, $\alpha(h)$	= 1·0
Maximum rooting depth, $Z_{r_{max}}$	= 60 cm
Days to maturity of crop, DTM	= 150 days
Days after planting, DAP	= 1 day
Soil water pressure head, $h_b(t)$	= − 300·0 cm
Prescribed initial head, $h_0(z, 0)$	= − 300·0 cm

The temporal variation of moisture content with depth at various times is presented in Figure 1. The results show that the moisture content in the soil progressively decreases with time. This change is more predominant in the upper few nodes in the initial period of simulation, however with time, the depth of the root zone too increases and hence the number of nodes along which the root water extraction function is lumped also increases. The temporal variation of root length is shown in Figure 2 in which the maximum root depth of 60 cm is achieved in about 150 days.

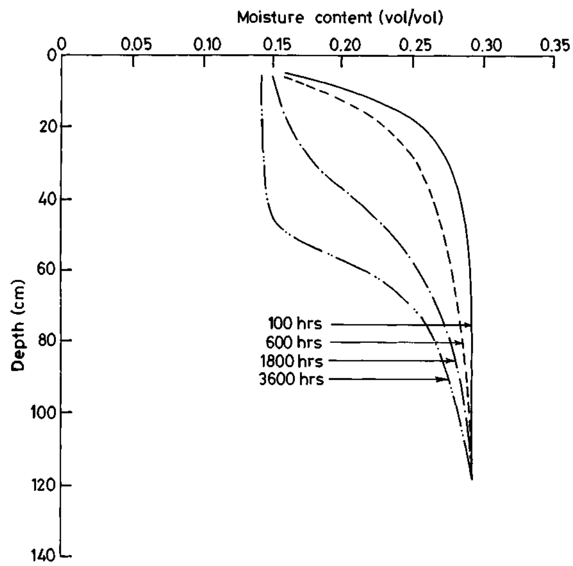

Figure 1. Variation of moisture content in soil with depth

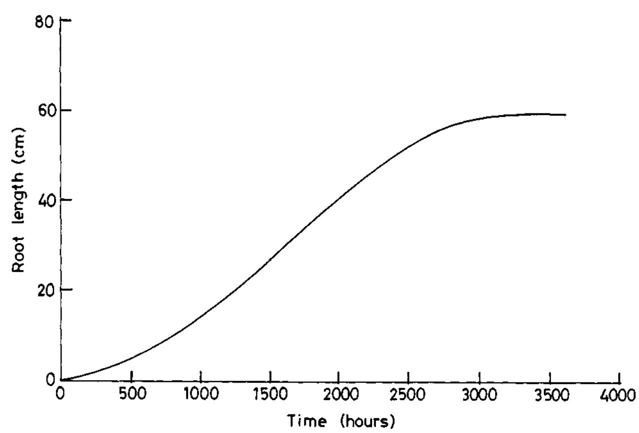

Figure 2. Root length versus time

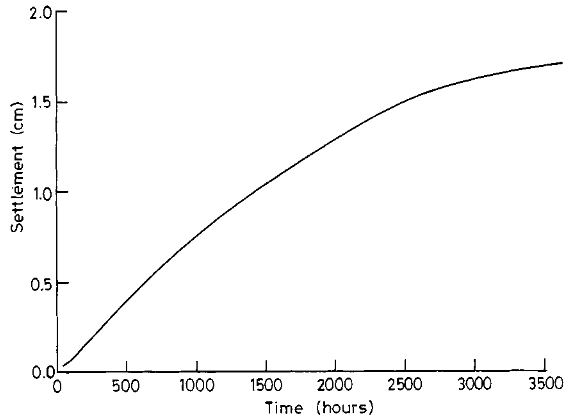

Figure 3. Temporal variation of settlement of soil column

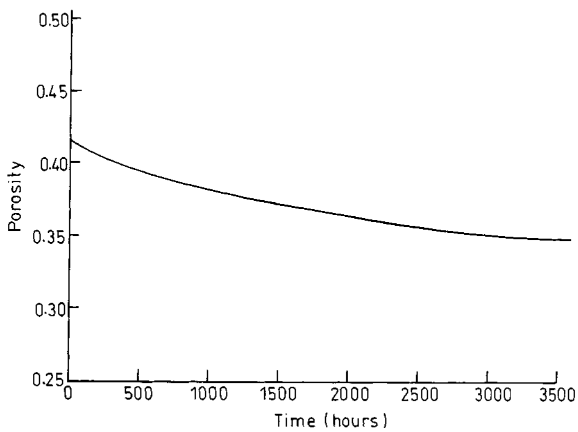

Figure 4. Variation of porosity of soil with time at 60 cm depth

The settlement is high in the initial stage, Figure 3, but gradually slows down and the consolidation ends after about 3600 h, during which time the porosity ceases to change, Figure 4. The maximum settlement of about 1·75 cm was achieved after 3600 h and a reduction in porosity equivalent to 16·5 per cent is obtained during the same duration.

The total water uptake by the roots at various times is depicted graphically in Figure 5. The root water extraction at a depth of 10 cm at the end of 1800 h was 1·5 times the water uptake after 3600 h. Moreover, the soil moisture content reduces with time as the root water extraction progresses.

CONCLUSIONS

The governing equations were solved by the finite element method to determine settlement of soils due to the uptake of water by roots of plants. The results show that the porosity of the soil

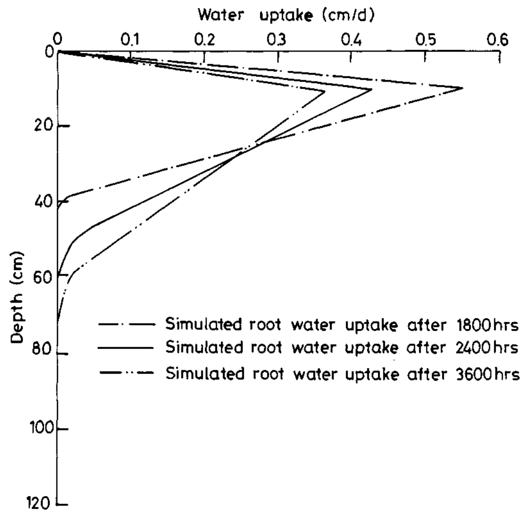

Figure 5. Extraction of water by roots versus depth

changes as the roots take up water to meet the transpiration demand of plants having a large leaf area index.

This model can be made to simulate more realistic values by including a time variant spatial root distribution function and the actual water application schedule. The potential transpiration rate based on the changing climatic conditions can also be used to improve the model. The model could also be used to study the movement of slab-on-grade shallow foundations which heave during the rainy season and shrink during periods of drought when the soil loses its moisture due to evaporation

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